# HIGH-PERFORMANCE PLASMAS WITH SMALL ELMS AT LOW COLLISIONALITY IN JET-ILW

2 experimental sessions performed June/August 2023

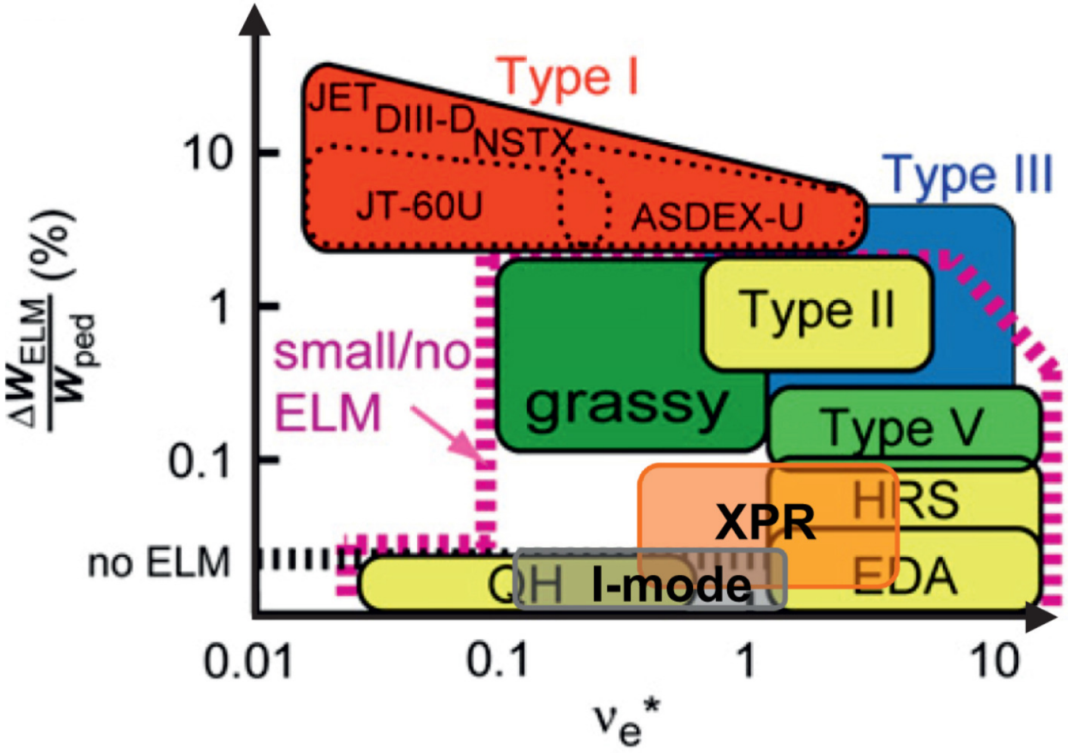
Presented by E. de la Luna (CIEMAT, Spain)
M. Dunne, P. Lomas, C. Reux, E.R. Solano, J. García, M. Faitsch,
M. Poradzinski, G. Pucella and JET contributors

Laboratorio Nacional de Fusión

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

# Small ELMs at low collisionality in JET-ILW

*Figure from E. Viezzer, NME 2023 (adapted from K. Kamiya et al, Plasma Phys. Control. Fusion 49 (2007) S43)*




- ELM control essential in ITER to avoid damage to PFCs:
  - operation with no-ELMs or small ELMs become attractive… but
  - accessing small ELMs in the ITER baseline scenario. ($H_{98}$ =1, $\beta_N$ =1.8, $\beta_{pol}$ <1 and $q_{95}$ ~3) at reactor-relevant conditions, such as low collisionality, is very challenging

→ **Operation at low or <u>no-gas</u> in JET-ILW allows access to good energy confinement with small ELMs in the baseline scenario at $q_{95}$=3.2 (3 MA/2.8 T) and $\beta_N$=1.8-2**

→ Initial experiments done in 2019, 2 additional sessions performed in 2023

# Best performing BSE discharge, so far

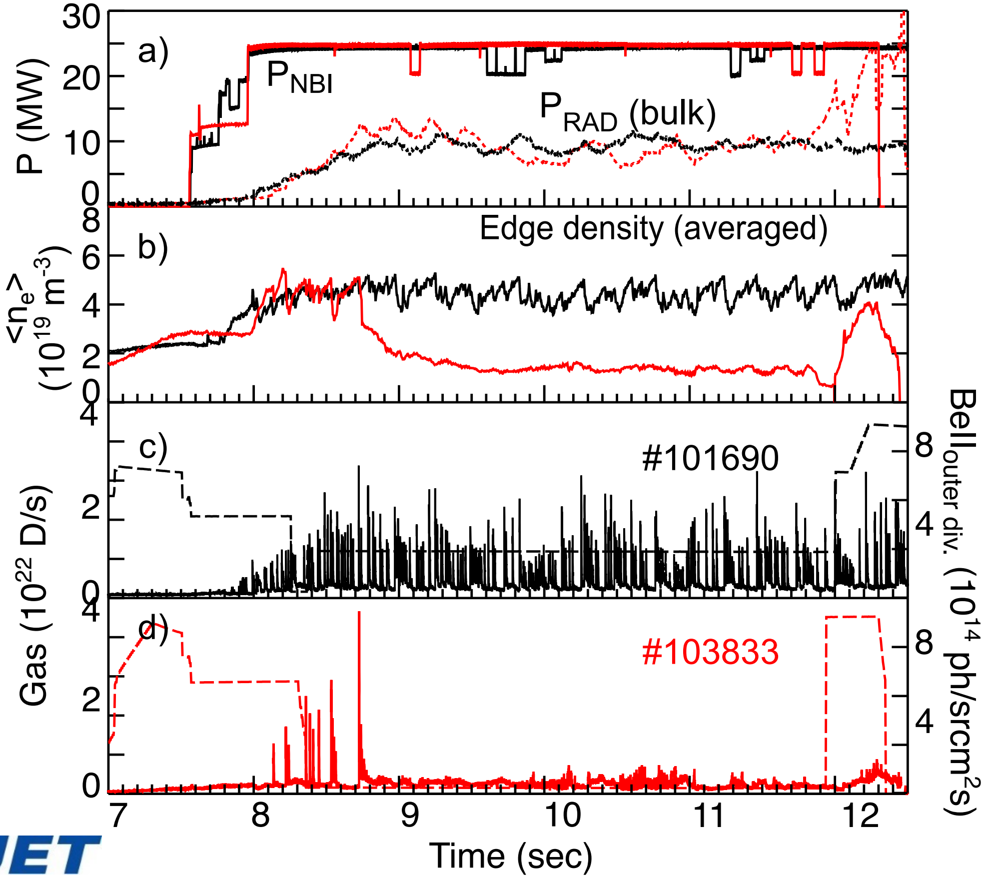
- Low $q_{95}$ =3.2 (3 MA, low triangularity)
- Low edge collisionality ($\nu^*$~0.1)
- Small ELMs
- In 2019:Stationary density levels, no core W accumulation

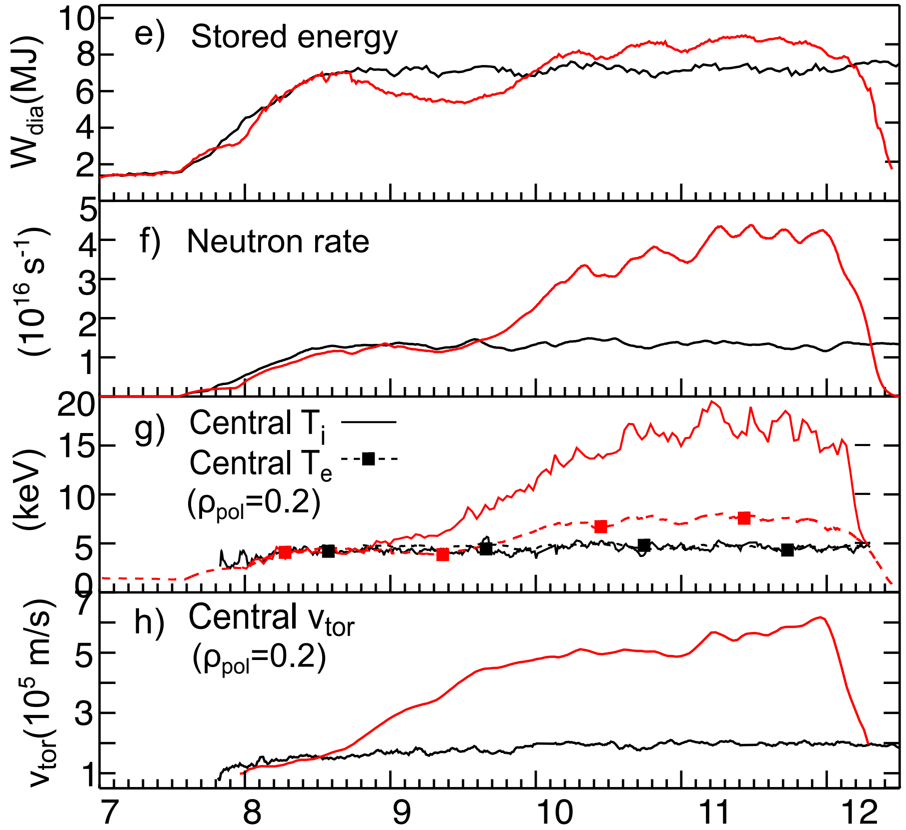
➢ In 2023: $T_i$ (neutron rates) and stored energy reach quasi-stationary conditions for more 1-1.3 s (~ 5-6 $\tau_E$)

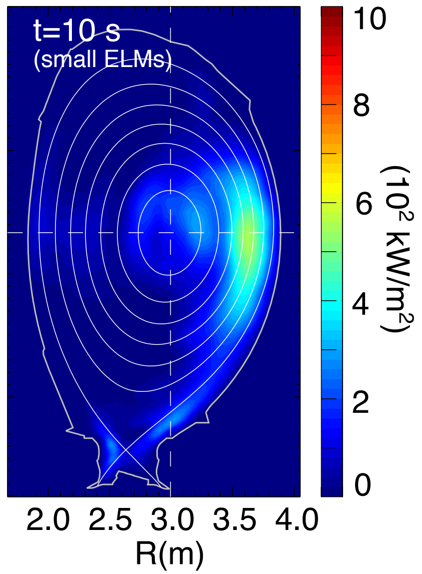
Compared to conventional ELMy H-mode:

- low plasma density (35% $n_{GW}$)
- better confinement and stronger rotation
- higher $T_i$ (at pedestal and in core, with $T_I$>>$T_e$),
- higher DD neutron rates

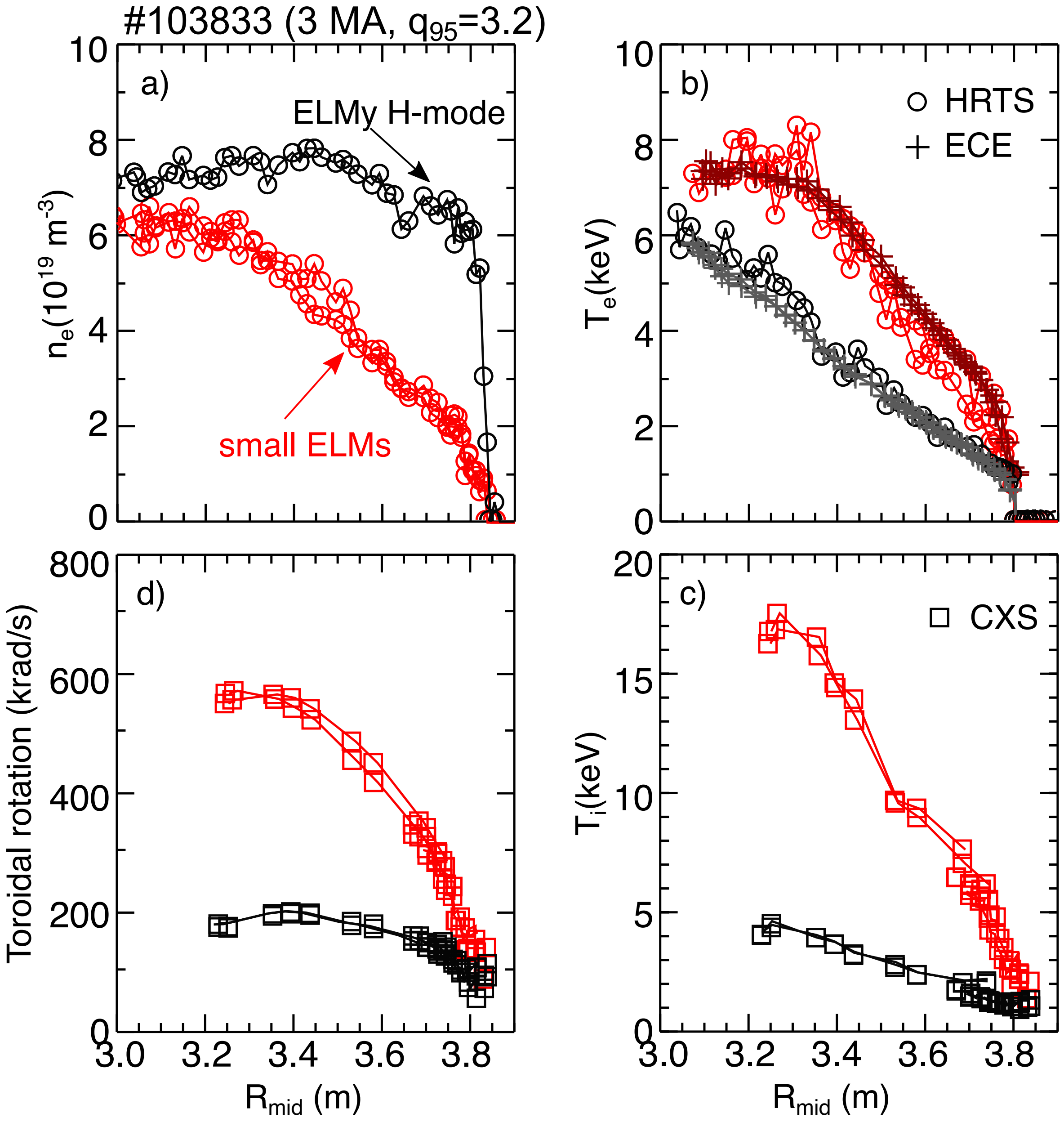
→ Similarities with 'hot-ion' in JET-C but also clear differences



# High performance plasmas at low pedestal collisionality




Small ELMs H-mode (no gas) compared with ELMy H-mode (gas fuelled):

- lower density and stronger density peaking
- higher $T_i$ and $T_e$, starting from pedestal, with $T_i >> T_e$
- higher rotation & rotation shear

→ Confinement above type I ELMy H-mode, with similar pedestal pressure but higher core pressure

→ Density for the no-gas case ($f_{GW}$=35%) is much lower than that expected in the ITER baseline scenario but similar pedestal collisionality ($\nu_{e,ped}$=0.1)

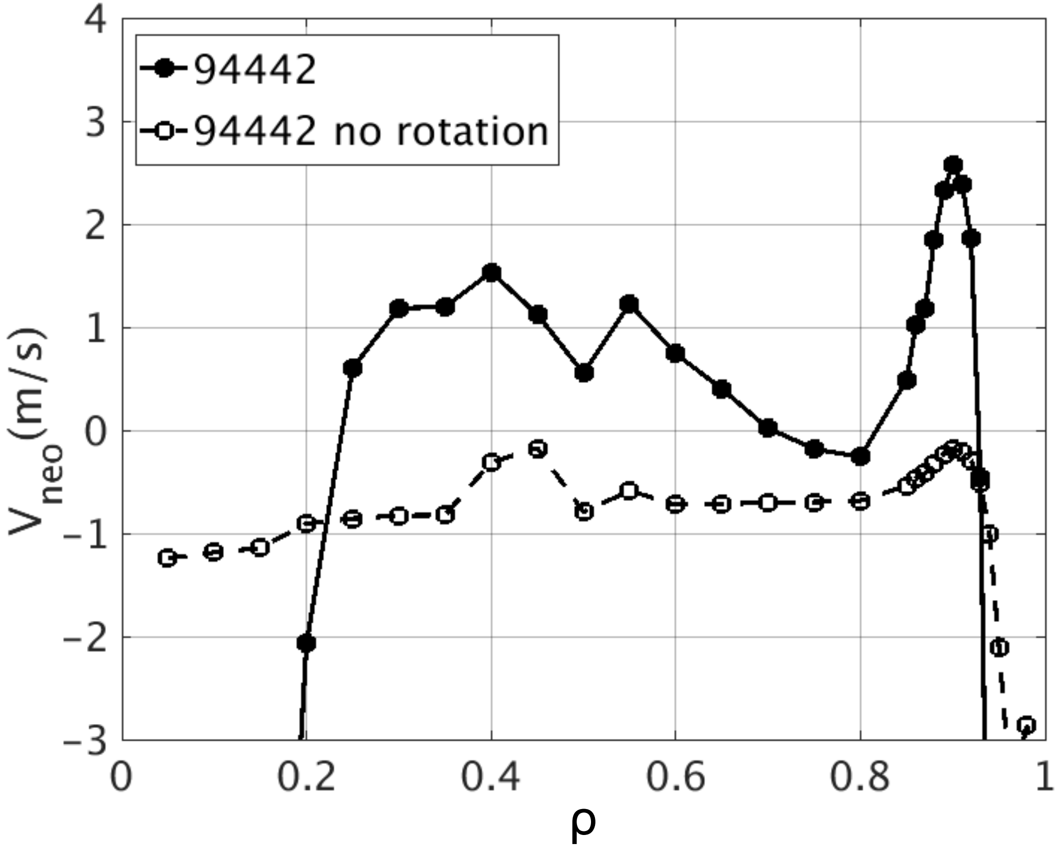
Gyrokinetic analyses [1] have shown that the improved core energy confinement is facilitated by favourable conditions for ITG driven turbulence stabilisation ($T_i/T_e$>1, impurity dilution at the edge, ExB shear)

[1] E. de la Luna, submitted for publication

# Edge temperature screening as expected in ITER

Neoclassical convective flux modelled with NEO

**Neoclassical convective velocity**

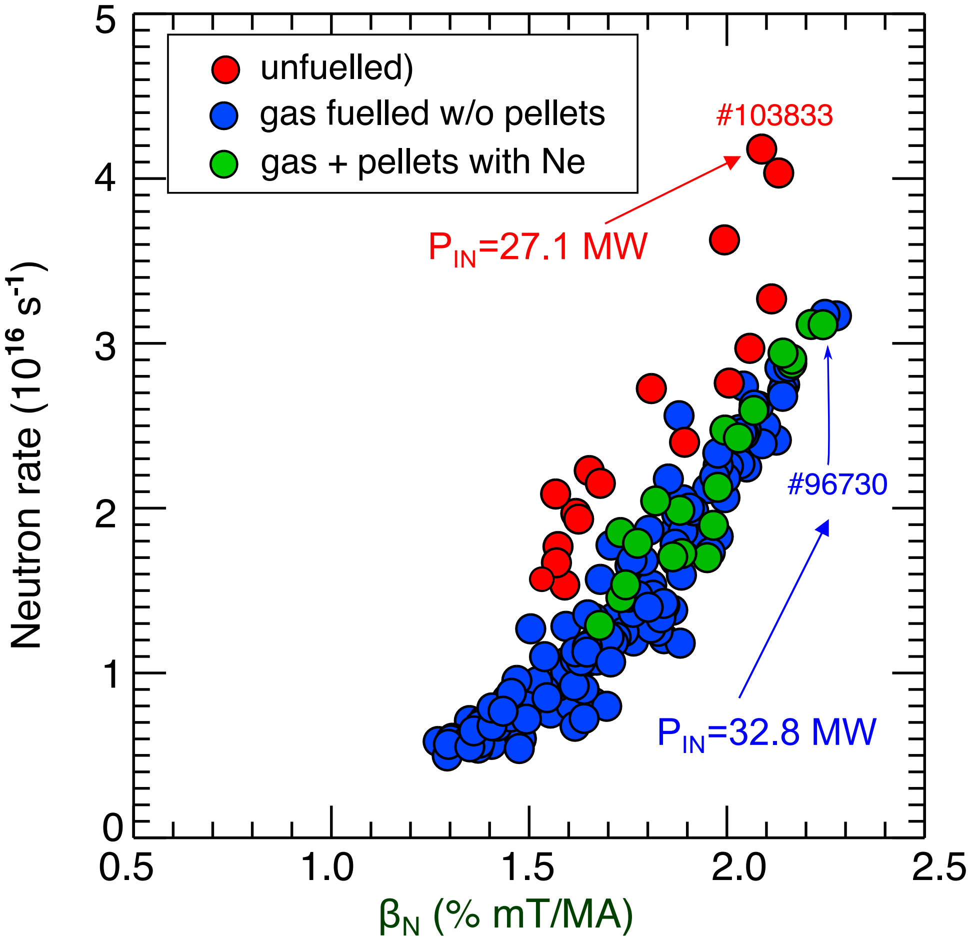



- Toroidal rotation acts positively on impurity transport causing a sign reversal of the W pinch from negative (inward) to positive (outward) [1] → core impurity screening. Consistent with the lack of W accumulation observed in the small ELMs regime with no gas
- Confirmed by recent modelling: enhanced temperature screening due to strong rotation obtained at low collisionality [2]. Impact on ITER expected to be small (low rotation)
- Significant W pinch at the top of the pedestal → Edge screening at low collisionality as expected in ITER (also reported in hybrid plasmas [3])


[1] J. García et al., Physics of Plasmas 29 (2022) 032505
[2] D. Fajardo et al., Plasma Phys. Control. Fusion 65 (2023) 035021
[3] A. Field et al., Plasma Phys. Control. Fusion 65 (2023) 035021

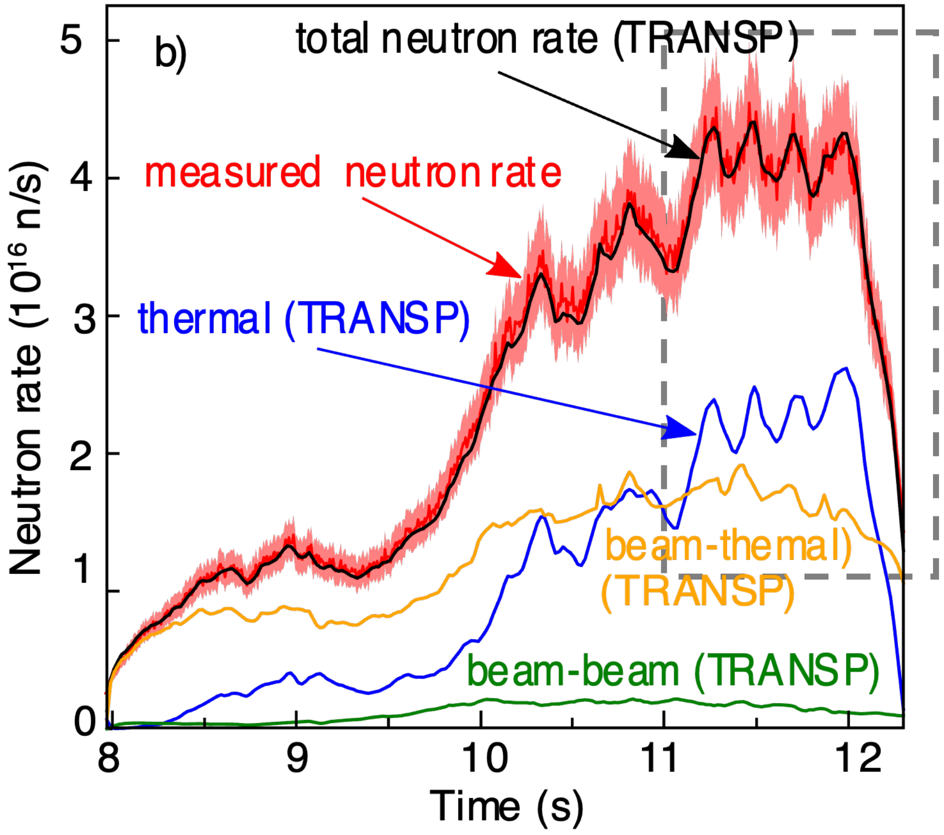
# Unfuelled BSE discharge produced the highest D-D fusion yield (~4×10[16] s[-1]) so far achieved in the baseline scenario

Baseline database (2019-2023): 3 MA/2.8 T ($q_{95}$=3.2), low triangularity, divertor corner configuration




Very good agreement between measured neutron rates and stored energy and TRANSP results using kinetic profiles

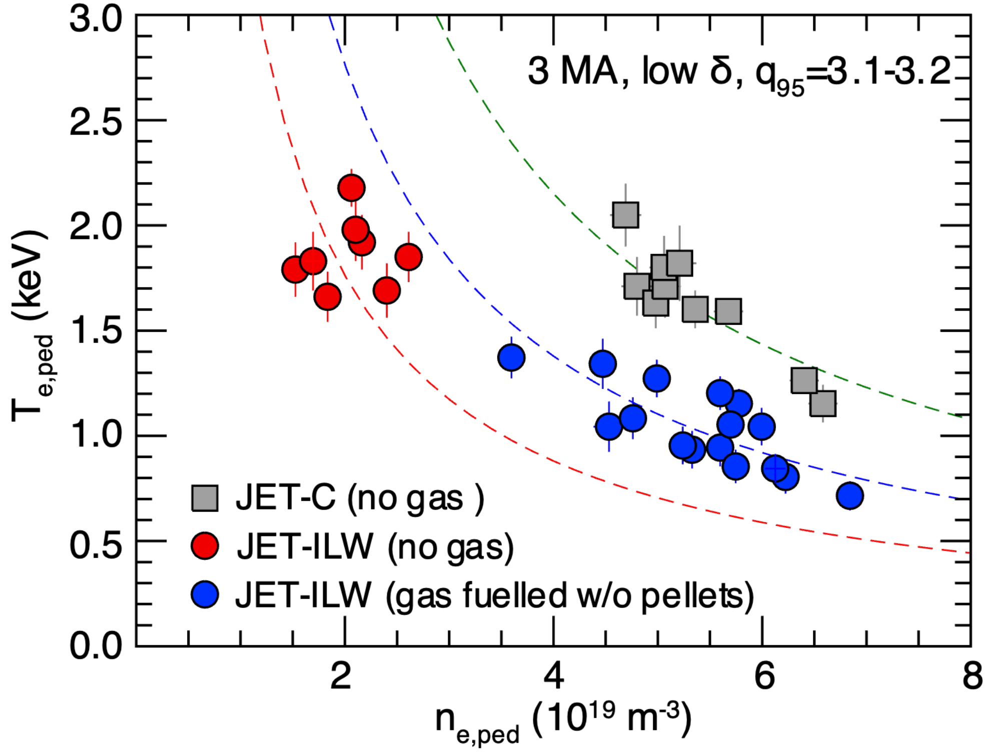
***~55% of neutrons produced by thermal reactions***

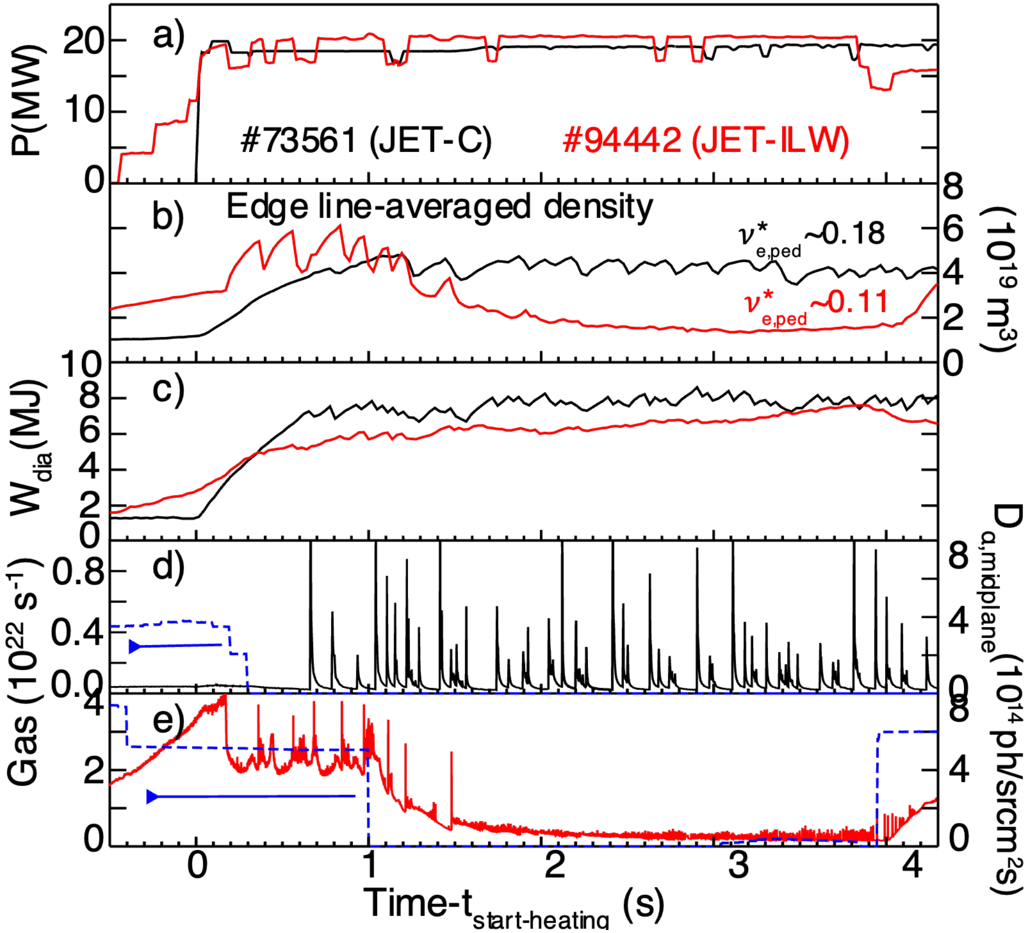



*Courtesy of F. Rimini*

# Impact of wall materials on the access to small ELMs

’natural’ density (no gas injection, fuelling provided only by NBI) in JET-C is about twice that seen in JET with the Be/W-wall

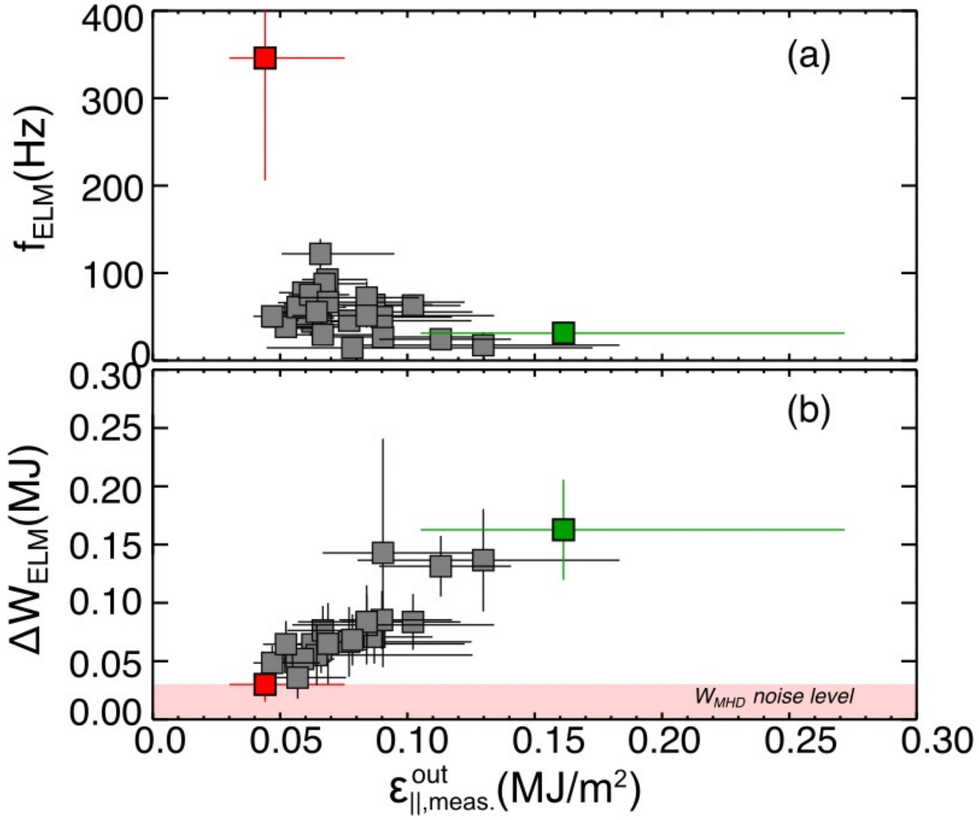



**The lower recycling and wall retention of the Be-wall allows access to a low-density regime (in the absence of external gas injection) that was not accessible with the C-wall, thus explaining why this small ELM regime was not discovered sooner**

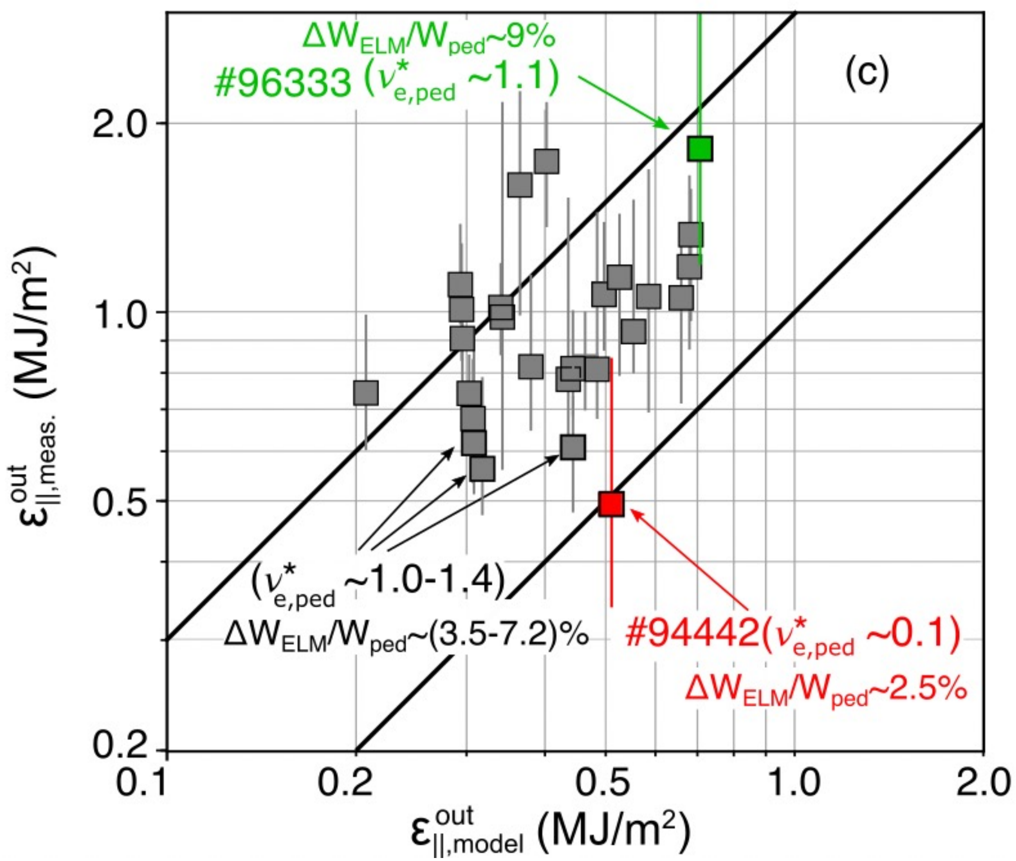
# Substantial reduction of divertor head loads (outer target)

- Smalls ELMs in the unfuelled BSE regime have $\Delta W_{ELM}$ within the noise of the fast $W_{MHD}$ signal (~30 kJ):
  - $\Delta W_{ELM}/W_{MHD}<0.5$ % and $\Delta W_{ELM}/W_{ped}<3$ %
- Very limited data so far due to damage in the divertor tile observed by the IR camera



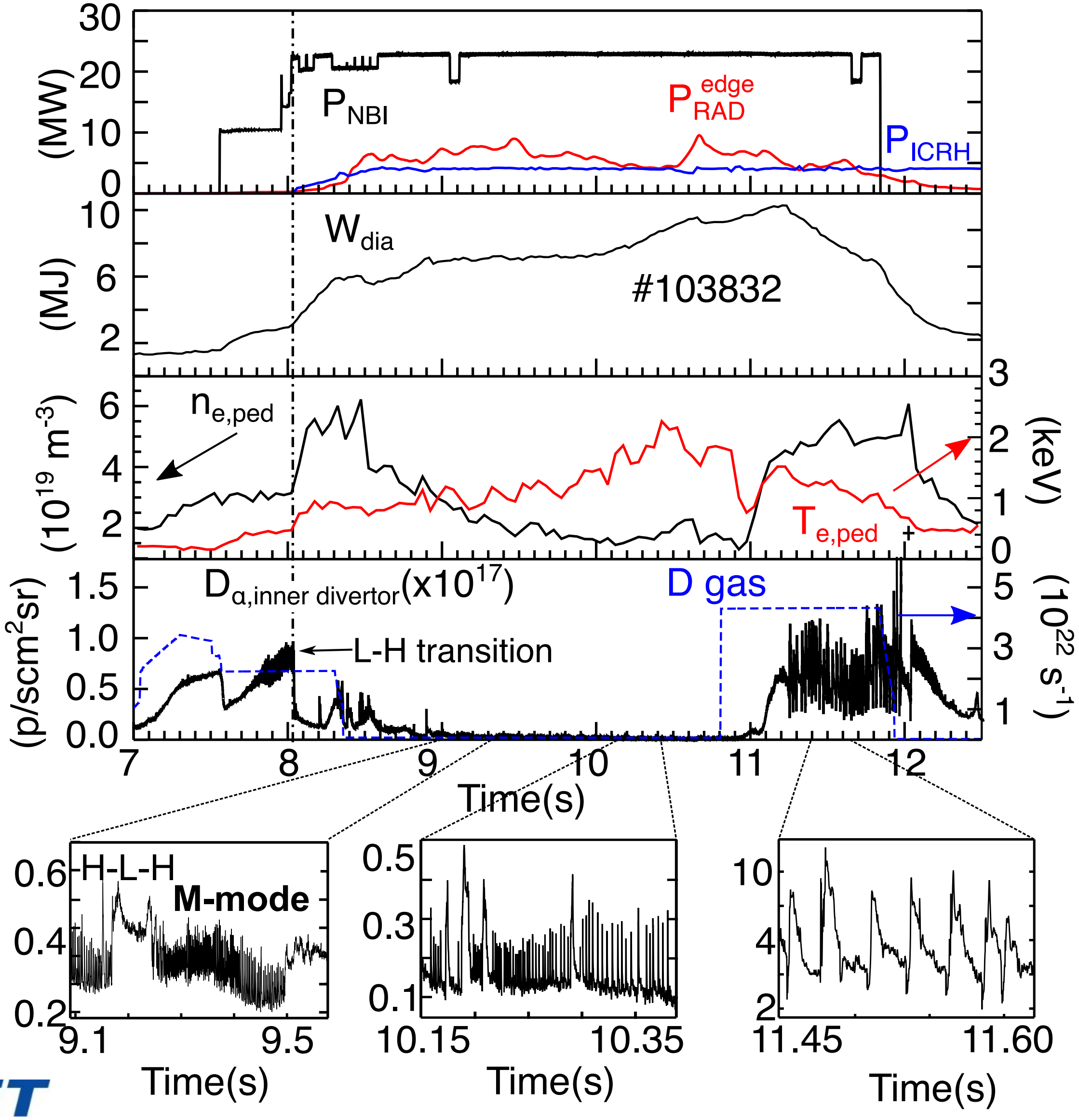

*E. de la Luna et al. (submitted for publication)*

ELMy H-mode D plasmas database from M. Faitsch, Nuclear Fusion 2023

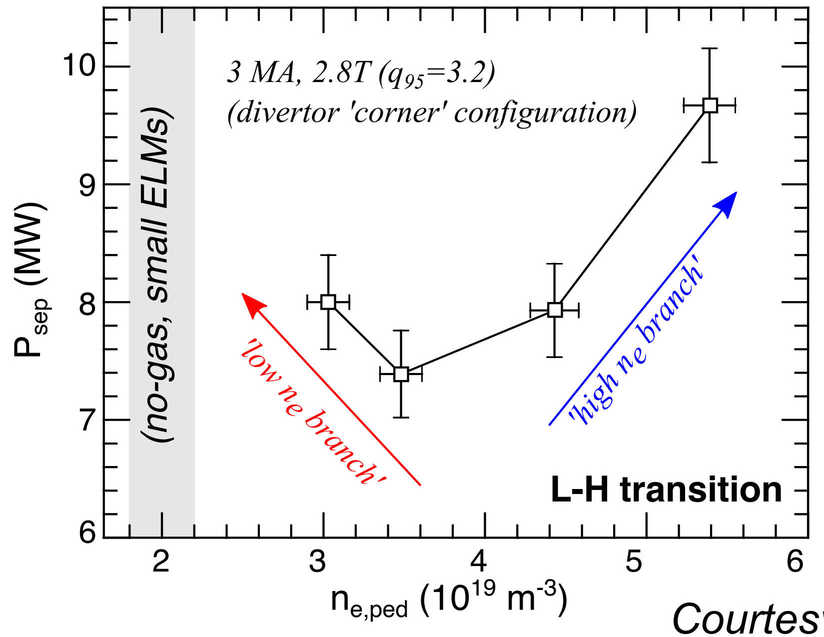


# Operation at $P_{IN}$ marginally above $P_{LH}$ (‘low density branch’)

Plasma shape: single null, low triangularity, with favourable ion ∇B drift for H-mode access.

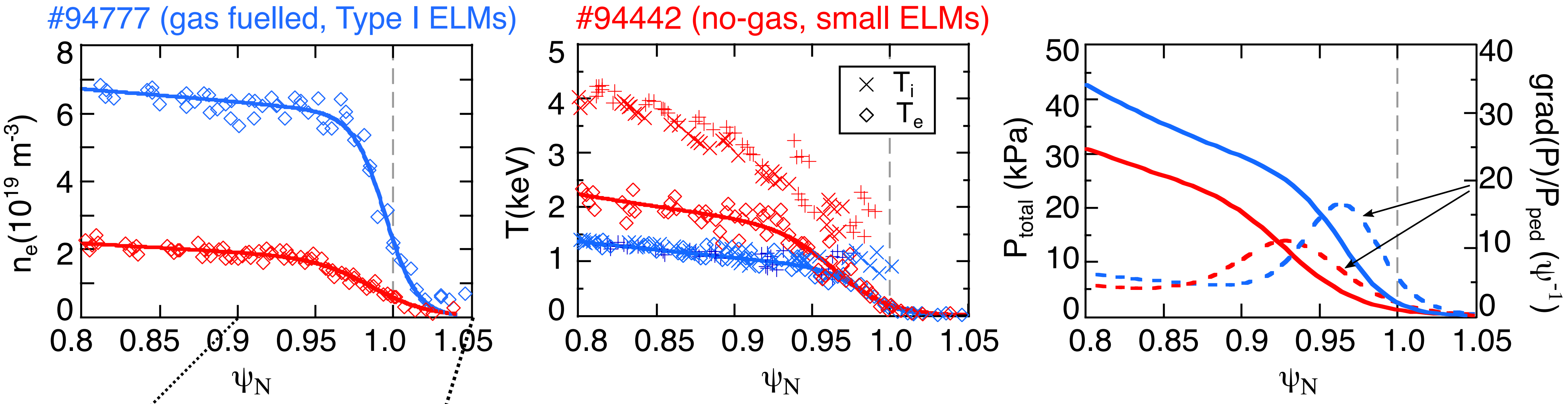


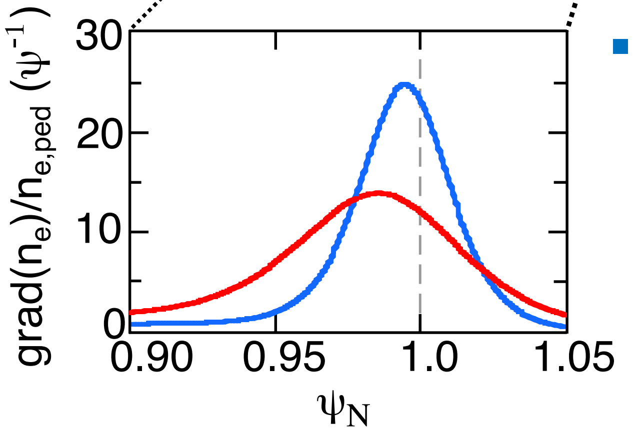

- $D_\alpha$ divertor signals indicate operation at $P_{IN}$~$P_{LH}$, despite $P_{sep}/P_{LH}^{ITPA-08}$>1.5
- Plasmas with no-gas and small ELMs operate in the ‘low density branch’ of the L-H threshold power




*Courtesy of E. Solano*

# I-mode like pedestals: H-mode like pedestals in $T_e$&$T_i$ but weak density gradient



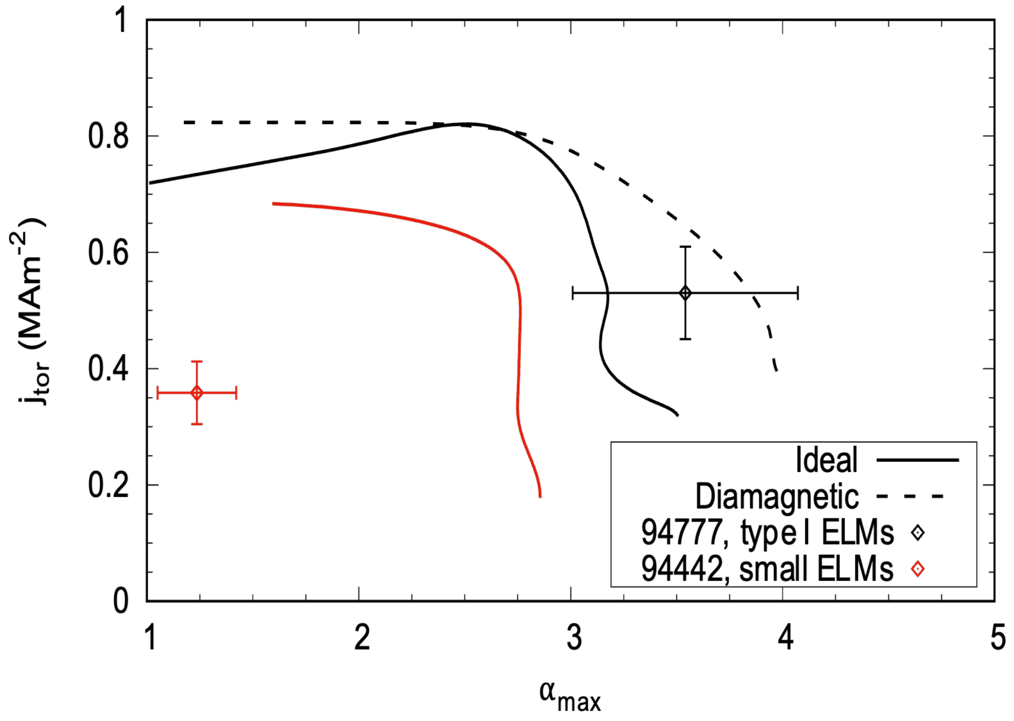



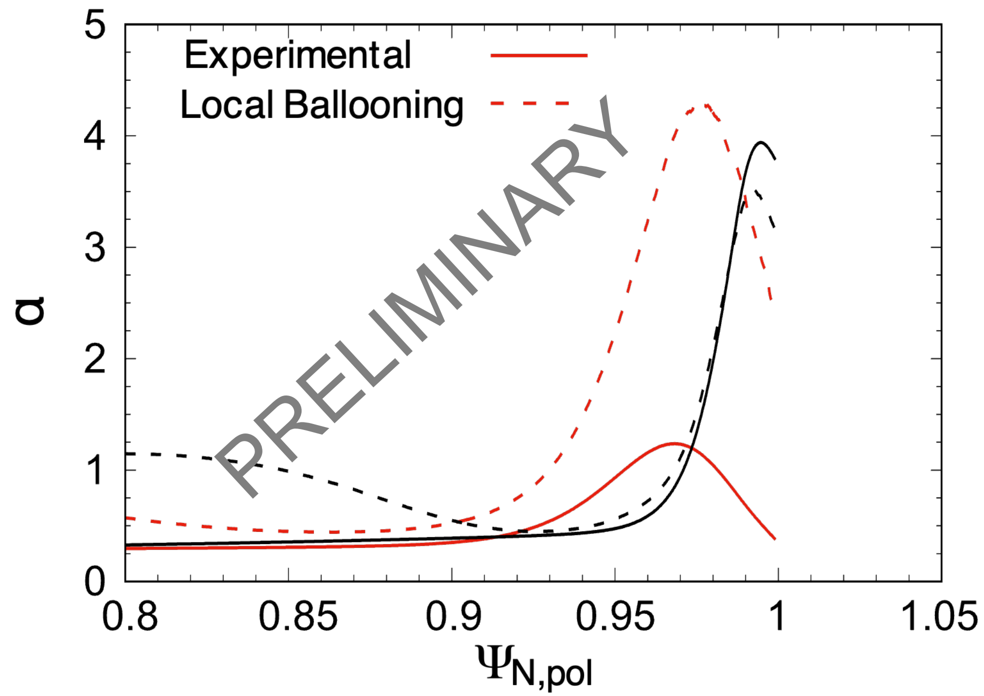

- Compared to the ELMy H-mode plasma, the discharge with small ELMs has:
  - similar $P^{PED}$ (lower $n_e^{PED}$, higher $T_e^{PED}$, $T_i^{PED}$)
  - comparable maximum $\nabla T_e$ → the higher $T_e^{ped}$ is due only to the wider width
  - wider pedestals, significantly lower maximum $\nabla n_e$ & $\nabla p_e$.
  - position of maximum gradient shifted inwards (due to wider width) → improved pedestal stability
  - reduced edge current (due to the reduction in $\nabla n_e$ )

# H-mode pedestals in the no-gas H-mode regime are P-B stable

**Pedestals in the no-gas regime are found to be stable to P-B modes, consistent with the lack of large ELMs**
The reduction in $\nabla n_e$ reduces both the drive for the ballooning ($\nabla P$) and the peeling ($J_{edge}$) modes

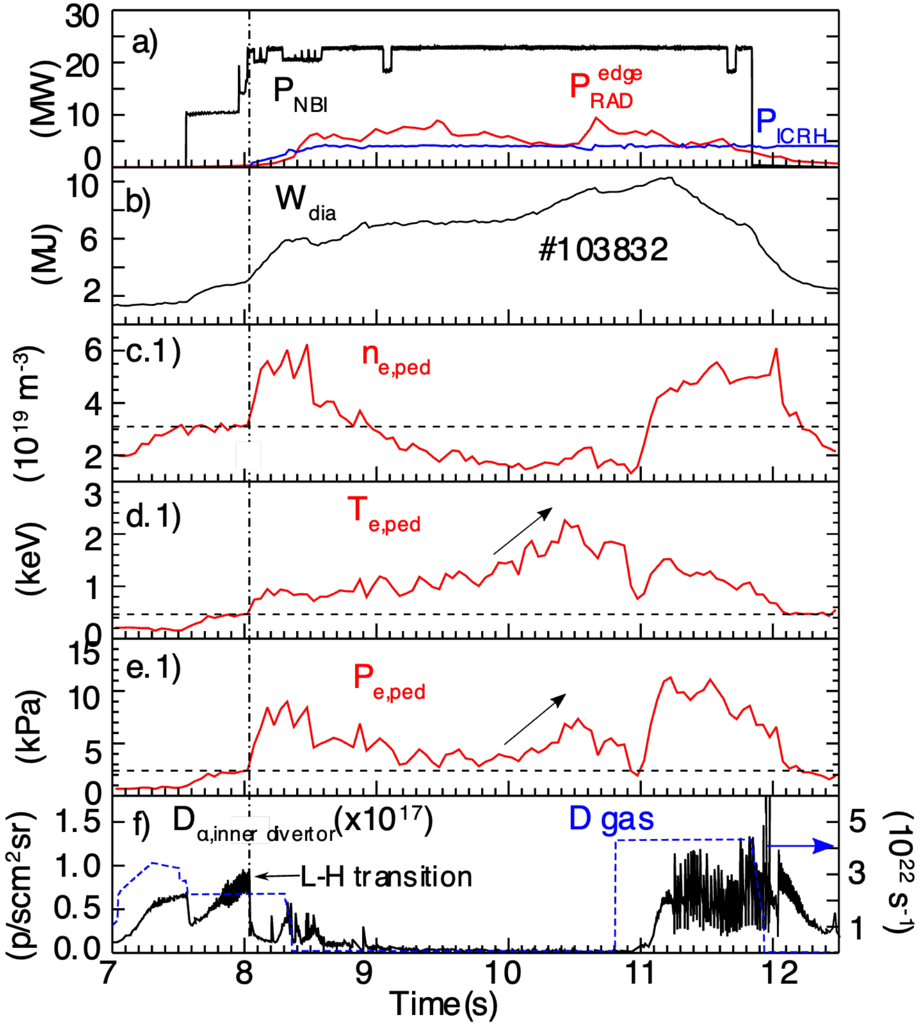
Local balllooning analysis has started. Initial analysis shows that for the small ELMs discharge both max. $\nabla P$ region and separatrix are stable

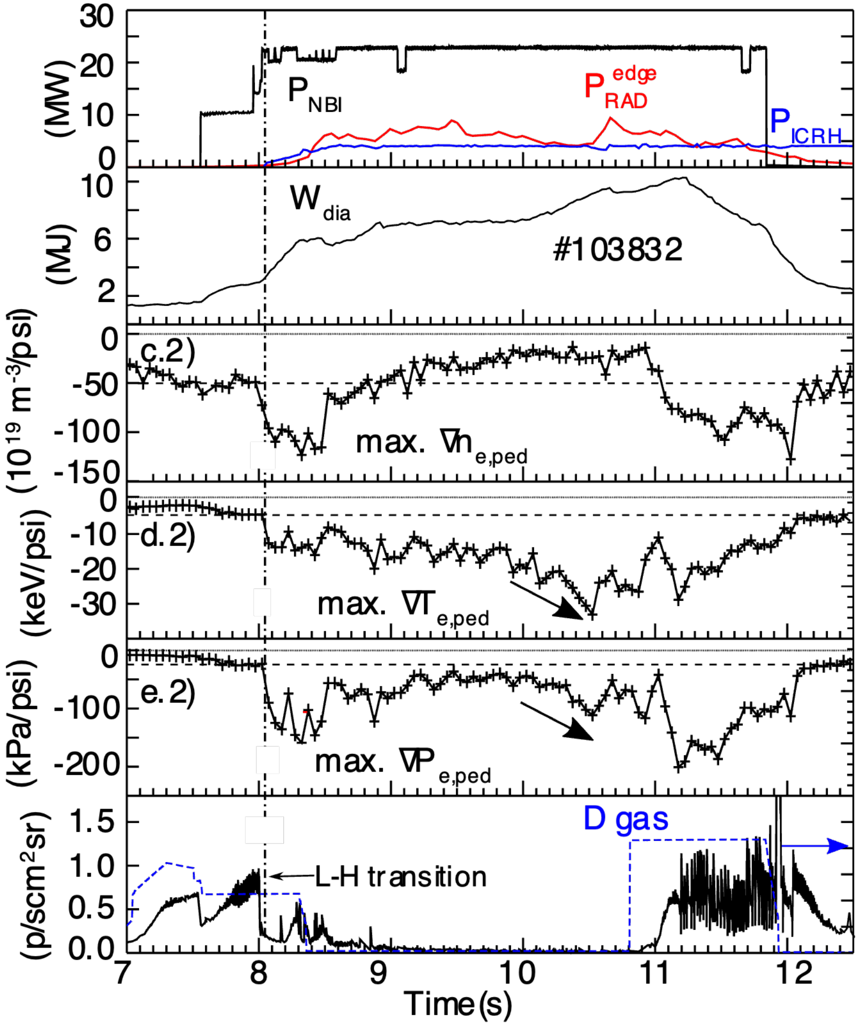


# Pedestal not limited by MHD as in the type I ELMy H-mode

**Edge pedestal gradients are not fixed by MHD stability limits, as in the case of the ELMy H-mode, but are most likely transport limited through a balance between the neoclassical and the turbulence transport**



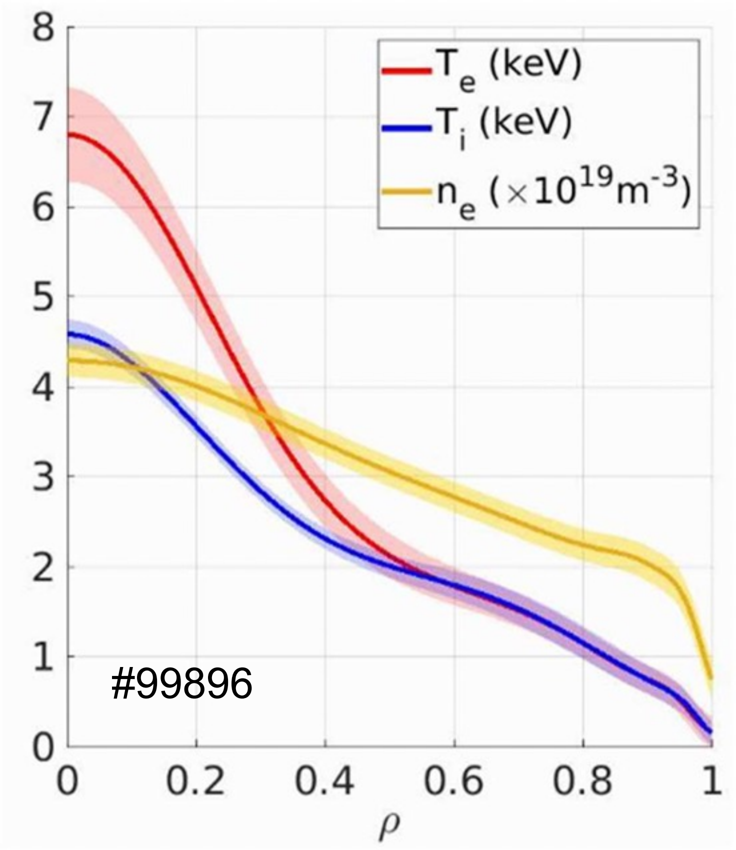

Small ELMs maintained as $T_i$ & $T_e$ increase at constant $P_{IN}$ (improved confinement)

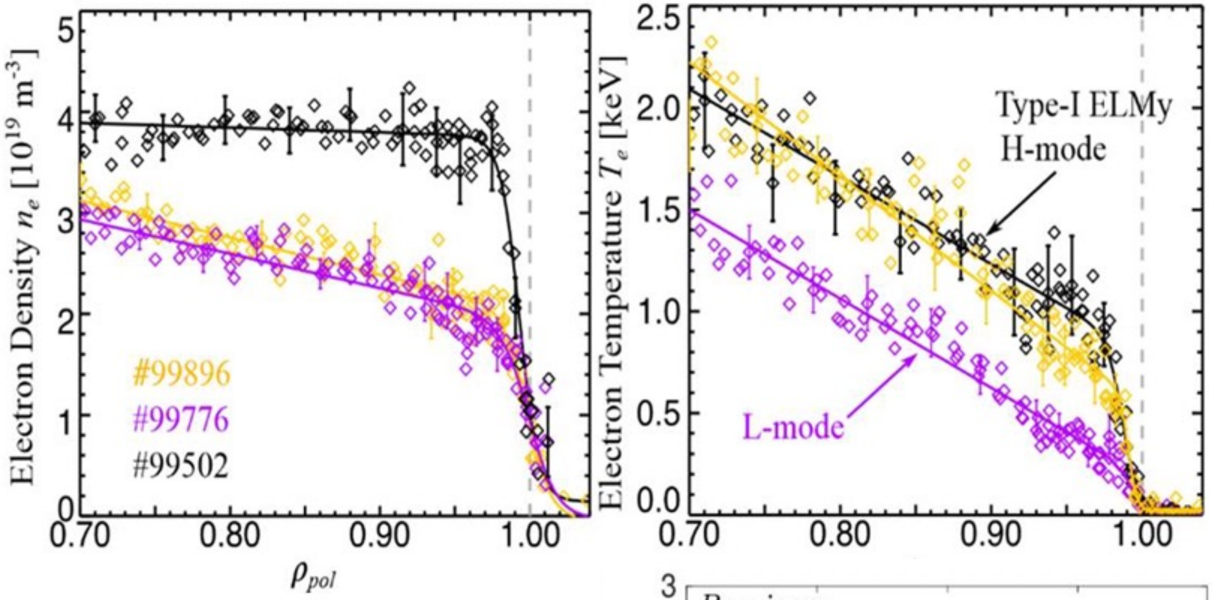
Type I ELMs reappear with increasing density (gas fuelling)

I-mode like pedestals but not WCM observed

# I-mode like pedestals with small ELMs also observed in plasmas with high electron heating and low torque

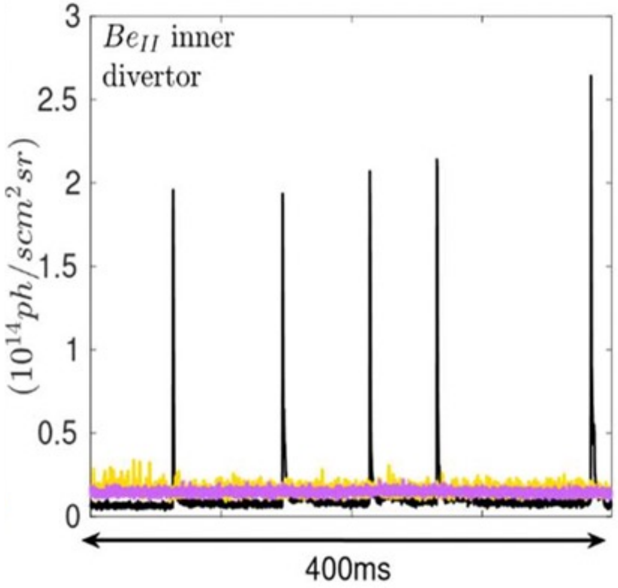
D-T plasmas (1.9MA, 2.8 T, $f_{GW}$=0.45)
High electron heating and low torque (low NBI + ICRH): $T_e/T_i$~1.4, Mach=0.12




- Similar to I-mode but with differences:
  - favourable ion ∇B drift for H-mode access
  - no sign of edge WCM

- Similarly seen before in JET [Delabie APS16] during low density H-mode transitions




[J. Garcia, Y. Kazakov arXiv:2309.11964]

# Summary

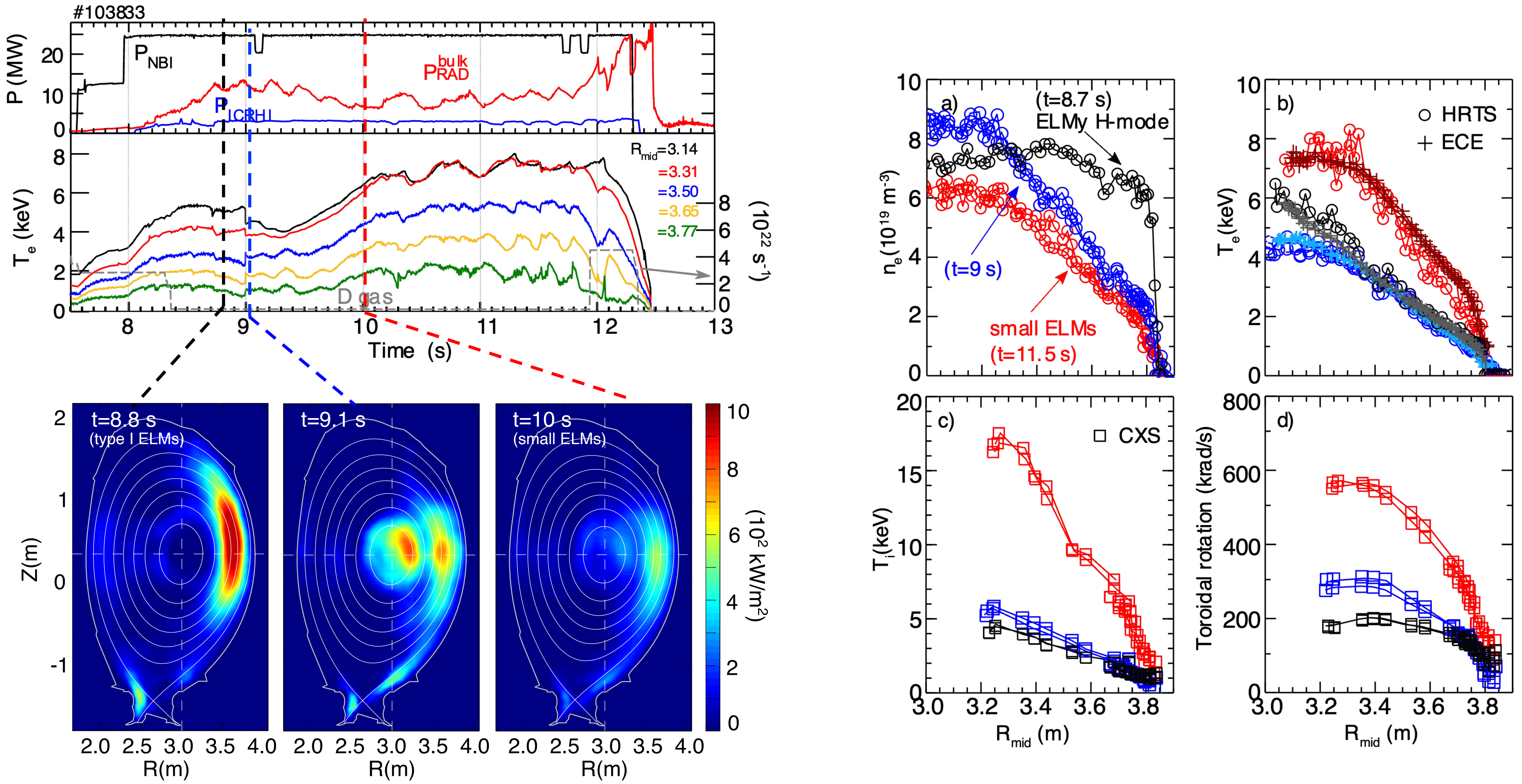
- Improved discharge reproducibility and extension of the quasi-stationary high performance phase. Neutron rate record in baseline plasmas at 3 MA, mainly due the high $T_i$ core (and pedestal) values
- Stability analysis is ongoing (including the impact of gas puff in the re-appearance of type-I ELMs): $T_{e,ped}$>1.7 keV and Ti,ped~3.5 keV, steep $T_e$ and $T_i$ pedestal gradients and wide density pedestal + operation close to L-H transition ('low density branch' of $P_{LH}$) → 'I-mode like' but not WCM observed
  - I-mode like pedestals + small ELMs observed in plasmas with ion and electron heating
- Very good results despite the limited experimental time allocated, BUT high disruptivity …..
- Analysis of high disruption rate in progress:
  - Two main causes:
    - radiative edge cooling, correlation with strike point sweeping is under investigation
    - operational limits imposed by low-density operation (heat loads on Be-limiters, NBI shine-through)
  - BUT there is room for improvement (increase in the outer GAP, operate at slightly reduced NBI power, removal of specific PINIs)
- **Unfuelled Baseline scenario with no- or very small ELMs still in development phase, not enough time to optimize the termination, but remarkable confinement results**

# Plans for 2024

- Outstanding challenges regarding reactor relevance include low-density operation, with $f_G \leq 0.4$, ($f_G = \overline{n_e}/n_G$), compared with the ITER baseline scenario $f_G$ ~0.85, and the compatibility with divertor detachment.
- Nevertheless, this unfuelled baseline scenario provides a unique opportunity to study:
  - pedestal physics and ELM dynamics high-temperature plasmas at the low edge collisionality values expected in ITER
    - physics mechanisms responsible for the small ELMs onset
    - common physics with I-mode plasmas
  - core and edge impurity control actuators: rotation in the core region and temperature screening at the edge drive by the steep $T_i$ pedestal profiles achieved
  - particle transport in the pedestal region in conditions with no or very low particle source (no-gas injection and low recycling), which should enable the validation of existing transport models and contribute to increasing the confidence in ITER performance predictions. This is an especially important topic to investigate since in future fusion devices, like ITER, fuel penetration beyond the separatrix, from gas, edge recycling or even from pellets, will be much weaker than in present devices.

# Additional material

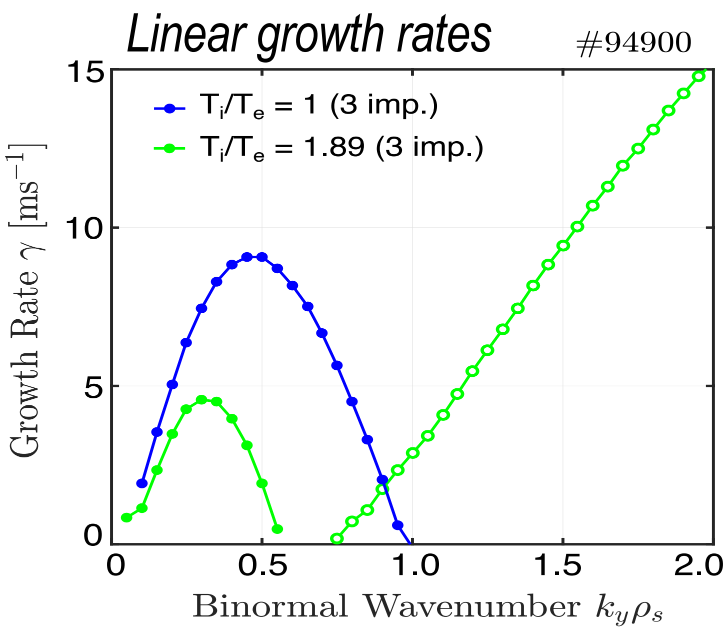
# Strong impact of rotation on core W transport

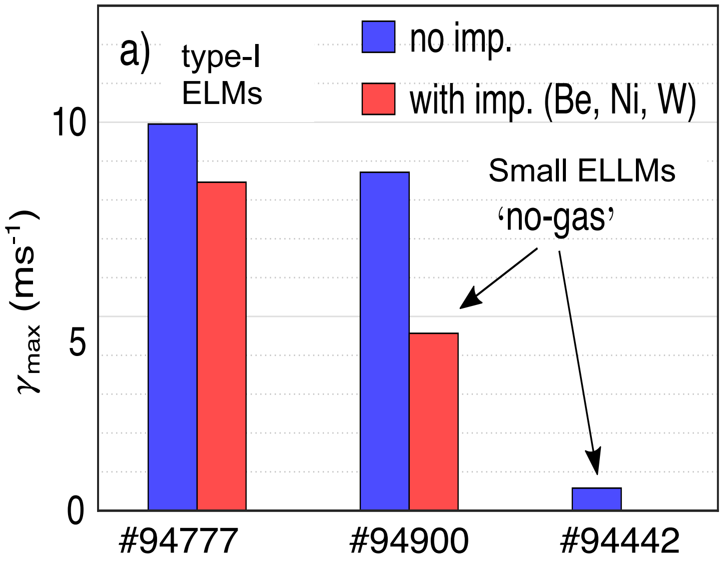


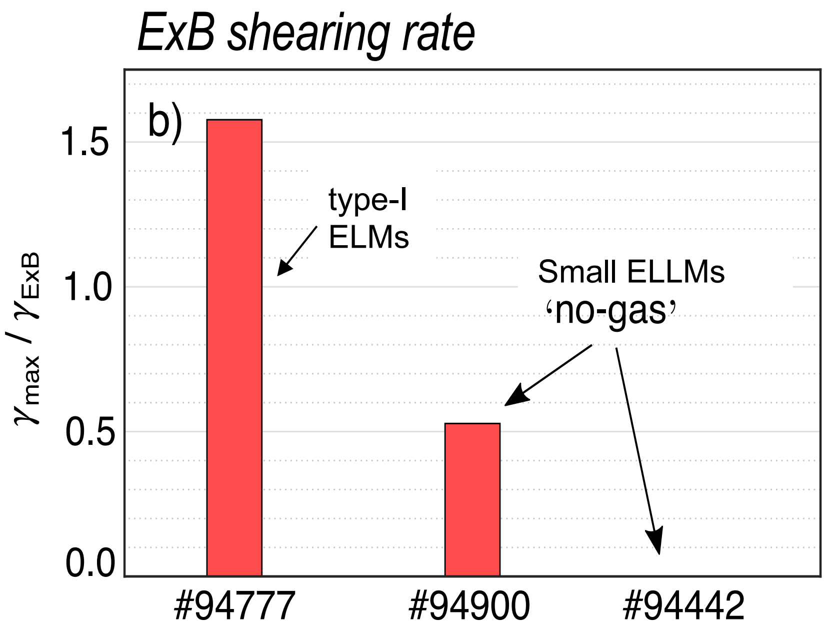

JET

# Turbulence analysis (linear analysis)

$T_i/T_e$~1.63 at $\rho_{tor}$=0.8 for #94900 (no-gas)
$T_i/T_e$~1 at $\rho_{tor}$=0.8 for #94777 (with gas)




**Three mechanisms to explain the enhanced ion confinement (ITG-dominated):**

- high $T_i/T_e$~1.63 starting at the pedestal top (compared to $T_i/T_e$~1 for the Type I ELMy H-mode)
- linear growth rate reduction via impurities (located at the edge, at the midplane, on the LFS)
- sheared ExB flows (increased rotation)

→ Similar results found in the JET baseline scenario with low gas & pellets *[Garcia, PoP-2022]*
→ and reproduced by integrated modelling with/without strong Ne seeding *[Giroud, IAEA-21,Gabriellini, NF-2023]*